

## 5. PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

### 5.1 PRODUCTION

Cobalt is the 33<sup>rd</sup> most abundant element, comprising approximately 0.0025% of the earth's crust. It is often found in association with nickel, silver, lead, copper, and iron ores and occurs in mineral form as arsenides, sulfides, and oxides. The most important cobalt minerals are: linnaeite,  $\text{Co}_3\text{S}_4$ ; carrollite,  $\text{CuCo}_2\text{S}_4$ ; safflorite,  $\text{CoAs}_2$ ; skutterudite,  $\text{CoAs}_3$ ; erythrite,  $\text{Co}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$ ; and glaucodot,  $\text{CoAsS}$  (Hodge 1993; IARC 1991; Merian 1985; Smith and Carson 1981). The largest cobalt reserves are in Zaire, Zambia, Morocco, Canada, and Australia; Zaire and Zambia have the richest deposits. Most of the U.S. cobalt deposits are in Minnesota, but other important deposits are in Alaska, California, Idaho, Missouri, Montana, and Oregon. Most U.S. cobalt resources are in subeconomic concentrations that are not expected to be feasible to exploit in the foreseeable future. Cobalt is also found in meteorites and deep sea nodules.

The production of pure metal from these ores depends on the nature of the ore. Sulfide ores are first finely ground and the sulfides are separated by a floatation process with the aid of frothers. The concentrated product is subjected to sulfatizing roasting, and the resulting matte is leached with water. The cobalt sulfate leachate is precipitated as its hydroxide by the addition of lime. The hydroxide is dissolved in sulfuric acid, and the resulting cobalt sulfate is electrolyzed to yield metallic cobalt. For the cobalt-rich mineral cobaltite, a leaching process with either ammonia or acid under pressure and elevated temperatures has been used to extract cobalt. The solution is purified to remove iron and is subsequently reduced by hydrogen in the presence of a catalyst under elevated temperature and pressure to obtain fine cobalt powder (Planinsek and Newkirk 1979).

Except for a negligible amount of byproduct cobalt produced from some mining operations, no cobalt is mined or refined in the United States. In addition to byproduct production, U.S. production is derived from scrap (secondary production). In 1998, 3,080 metric tons of cobalt was recycled from scrap. Since 1993, production has been supplemented by sales of excess cobalt from the National Defense Stockpile (NDS), which the government maintains for military, industrial, and essential civilian use during national emergencies. In fiscal year 1999, 1,960 metric tons of cobalt were released from the NDS. In 1995–1998, between 1,550 and 2,310 metric tons of cobalt were removed from the NDS annually. Cobalt is present in the ores mined for platinum group metals at the Stillwater Complex in southern Montana

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where cobalt is produced as a byproduct. The 1998 U.S. consumption of cobalt metal, organic and inorganic cobalt compounds, and purchased scrap (in terms of cobalt content) was 3,780, 1,910, and 2,720 metric tons, respectively (USGS 1998).

Current U.S. manufacturers of selected cobalt compounds are given in Table 5-1. Table 5-2 lists facilities in each state that manufacture, process, or use cobalt or cobalt compounds, the intended use, and the range of maximum amounts of these substances that are stored on site. In 1999, there were 695 reporting facilities that produced, processed, or used cobalt or cobalt compounds in the United States. The data listed in Table 5-2 are derived from the Toxics Release Inventory (TRI99 2001). Only certain types of facilities were required to report. Therefore, this is not an exhaustive list.

$^{60}\text{Co}$  is produced by irradiating natural cobalt,  $^{59}\text{Co}$ , with thermal neutrons in a nuclear reactor:  $^{59}\text{Co}(n,\gamma)^{60}\text{Co}$ . The neutron flux employed is  $10^{12}$ – $10^{15}$   $n/\text{cm}^2\text{-sec}$  and the conversion is 99%. The maximum activity obtained is  $3.7 \times 10^{13}$  Bq/g (1,000 Ci/g). Commercial  $^{60}\text{Co}$  sources are made into rods with double metal shielding. The individual sources have an activity of about  $2 \times 10^{14}$ – $6 \times 10^{14}$  Bq (6–15 kCi). The annual output of  $^{60}\text{Co}$  was about  $2 \times 10^{18}$ – $3 \times 10^{18}$  Bq (50–80 MCi) in the early 1990s. In 1991, there were 170 gamma irradiation systems operating in 45 countries having a total activity of about  $6 \times 10^{18}$  Bq (160 MCi) (Zyball 1993). Producers of  $^{60}\text{Co}$  include MDS Nordion in Canada, AEA Technology (formerly Amersham QSA) in the United Kingdom, and Neutron Products in Dickerson, Maryland.

$^{58}\text{Co}$  is not produced commercially. It can be produced by irradiating  $^{58}\text{Ni}$ , a stable isotope, with neutrons, followed by positron decay:  $^{58}\text{Ni}(n,\gamma)^{58}\text{Co}$ . It can be produced in a nuclear reactor or a cyclotron. Both  $^{60}\text{Co}$  and  $^{58}\text{Co}$  may be produced unintentionally in reactors. These are the dominant source of residual radiation in the primary circuit outside the reactor core of nuclear plants and are formed by neutron absorption of  $^{59}\text{Co}$  and  $^{58}\text{Ni}$ , both stable isotopes commonly used in plant construction materials (Taylor 1996).  $^{60}\text{Co}$  is a frequent major contaminant of cooling water released by nuclear reactors.

The  $^{60}\text{Co}$  activities for a typical pressurized-water reactor (PWR) and boiling water reactor (BWR) fuel assemblies are 150 and 37 Ci, respectively (DOE 1999). There are 78 PWR and 41 BWR reactors in the United States, several of which have ceased operation. The total projected inventory of  $^{60}\text{Co}$  for all

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**Table 5-1. Current U.S. Manufacturers of Cobalt Metal and Selected Cobalt Compounds<sup>a</sup>**

Company	Location
<b>Cobalt metal<sup>b</sup></b>	
Kennametal, Inc.	Latrobe, Pennsylvania
OM Group, Inc.	Cleveland, Ohio
Osram Sylvania Products, Inc.	Towanda, Pennsylvania
Stoody Company	St. Louis, Missouri
<b>Cobalt (II) acetate:</b>	
The Hall Chemical Co.	Arab, Alabama
	Wickliffe, Ohio
McGean-Rohco, Inc.	Cleveland, Ohio
OM Group, Inc.	Franklin, Pennsylvania
The Shepherd Chemical Co.	Cincinnati, Ohio
<b>Cobalt (II) carbonate:</b>	
The Hall Chemical Co.	Wickliffe, Ohio
IMC/Americhem	Shelby, North Carolina
McGean-Rohco, Inc.	Cleveland, Ohio
OMG Apex	St. George, Utah
OM Group, Inc.	Franklin, Pennsylvania
The Prince Manufacturing Company	Bowmanstown, Pennsylvania
	Quincy, Illinois
The Shepherd Chemical Co.	Phillipsburg, New Jersey
	Cincinnati, Ohio
<b>Cobalt (II) chloride:</b>	
The Hall Chemical Co.	Wickliffe, Ohio
IMC/Americhem	Shelby, North Carolina
Johnson Matthey, Inc., Alfa Aesar	Ward Hill, Massachusetts
McGean-Rohco, Inc.	Cleveland, Ohio
OM Group, Inc.	Franklin, Pennsylvania
The Shepherd Chemical Co.	Cincinnati, Ohio
Union Miniere, Inc., Carolmet Cobalt Products Division	Laurinburg, North Carolina
<b>Cobalt (II) hydroxide:</b>	
The Hall Chemical Co.	Wickliffe, Ohio
McGean-Rohco, Inc.	Cleveland, Ohio
OM Group, Inc.	Franklin, Pennsylvania
The Shepherd Chemical Co.	Cincinnati, Ohio

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## Cobalt (II) nitrate:

The Hall Chemical Co.	Arab, Alabama
IMC/Americhem	Shelby, North Carolina
Johnson Matthey, Inc., Alfa Aesar	Ward Hill, Massachusetts
McGean-Rohco, Inc	Cleveland, Ohio
OMG Apex	St. George, Utah
OM Group, Inc.	Franklin, Pennsylvania
The Shepherd Chemical Co.	Cincinnati, Ohio
Union Miniere, Inc., Carolmet Cobalt Products. Division	Laurinburg, North Carolina

**Table 5-1. Current U.S. Manufacturers of Cobalt Metal and Selected Cobalt Compounds<sup>a</sup> (continued)**

Company	Location
Cobalt (II) oxide:	
The Hall Chemical Co.	Wickliffe, Ohio
IMC/Americhem	Shelby, North Carolina
OMG Apex	St. George, Utah
The Shepherd Chemical Co.	Cincinnati, Ohio
Cobalt (III) oxide	
The Hall Chemical Co.	Wickliffe, Ohio
Johnson Matthey, Inc., Alfa Aesar	Ward Hill, Massachusetts
Mallinckrodt Baker, Inc.	Phillipsburg, New Jersey
McGean-Rohco, Inc.	Cleveland, Ohio
OM Group, Inc.	Franklin, Pennsylvania
Cobalt (II) sulfate	
The Hall Chemical Co.	Arab, Alabama
	Wickliffe, Ohio
IMC/Americhem	Shelby, North Carolina
McGean-Rohco, Inc.	Cleveland, Ohio
OMG Apex	St. George, Utah
OM Group, Inc.	Franklin, Pennsylvania
The Prince Manufacturing Company	Bowmanstown, Pennsylvania
	Quincy, Illinois
The Shepherd Chemical Co.	Cincinnati, Ohio

<sup>a</sup>Derived from SRI 1999, receipt where otherwise noted. SRI reports production of chemicals produced in commercial quantities (defined as exceeding 5,000 pounds or \$10,000 in value annually) by the companies listed.

<sup>b</sup>U.S. members of The Cobalt Development Institute that are listed as producers of cobalt powder or hard metal products.

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**Table 5-2. Facilities that Produce, Process, or Use Cobalt or Cobalt Compounds**

State <sup>a</sup>	Number of facilities	Minimum amount on site in pounds <sup>b</sup>	Maximum amount on site in pounds <sup>b</sup>	Activities and uses <sup>c</sup>
AK	2	10,000	999,999	1, 5, 8, 13
AL	17	1,000	999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13
AR	6	1,000	99,999	1, 2, 3, 4, 5, 8, 9, 10
AZ	11	1,000	9,999,999	1, 2, 3, 4, 5, 6, 8, 9, 10, 11, 13
CA	18	1,000	999,999	2, 3, 4, 7, 8, 9, 10, 11, 13
CT	8	100	9,999,999	2, 3, 8, 9, 10, 12
DE	2	100	99,999	1, 5, 6, 11
FL	10	0	99,999	1, 3, 4, 5, 6, 7, 8, 9, 10, 13
GA	13	100	999,999	1, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13
IA	7	1,000	999,999	3, 4, 8, 9, 13
ID	1	100,000	999,999	1, 5
IL	25	0	9,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13
IN	25	100	9,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13
KS	5	1,000	99,999	1, 3, 5, 7, 8, 9, 11, 13
KY	16	1,000	999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13
LA	10	1,000	999,999	1, 2, 3, 5, 6, 7, 9, 11, 13
MA	6	1,000	999,999	1, 5, 9, 10, 13
MD	4	1,000	99,999	1, 2, 3, 5, 6, 7, 8
ME	1	10,000	99,999	9
MI	15	0	999,999	1, 2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13
MN	2	1,000	99,999	1, 6, 7, 8, 10, 11
MO	6	1,000	999,999	1, 2, 3, 4, 5, 6, 7, 9, 10, 13
MS	7	100	99,999	1, 3, 4, 5, 6, 7, 8, 9, 10, 11
MT	1	10,000	99,999	1, 3, 5, 6, 13
NC	17	1,000	999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13
ND	2	1,000	9,999	1, 5, 6, 13
NE	1	1,000	9,999	9, 12
NH	1	100	999	9
NJ	7	1,000	999,999	1, 3, 4, 7, 8, 9
NM	10	1,000	10,000,000,000	1, 2, 3, 4, 5, 6, 8, 9, 10, 12, 13
NV	12	1,000	9,999,999	1, 5, 6, 7, 8, 9, 10, 12, 13
NY	10	1,000	999,999	1, 2, 3, 4, 5, 8, 9, 10, 12

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**Table 5-2. Facilities that Produce, Process, or Use Cobalt or Cobalt Compounds  
(continued)**

State <sup>a</sup>	Number of facilities	Minimum amount on site in pounds <sup>b</sup>	Maximum amount on site in pounds <sup>b</sup>	Activities and uses <sup>c</sup>
OH	31	0	9,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13
OK	8	100	99,999	1, 2, 3, 4, 5, 7, 8, 9
OR	4	1,000	999,999	8, 10, 13
PA	31	0	9,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13
PR	2	1,000	99,999	9, 10
RI	1	100,000	999,999	9
SC	20	100	999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13
TN	13	100	999,999	1, 2, 3, 5, 6, 7, 8, 9, 11, 13
TX	22	0	999,999	1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13
UT	6	1,000	999,999	1, 2, 3, 4, 5, 6, 8, 9, 10, 13
VA	6	10,000	999,999	1, 2, 3, 5, 7, 8, 9
VI	1	10,000	99,999	11
WA	2	10,000	99,999	1, 3, 4, 5, 6, 10, 11, 12, 13
WI	11	0	999,999	1, 2, 3, 4, 5, 6, 8, 9, 10, 13
WV	7	100	999,999	1, 2, 3, 4, 5, 6, 8, 9, 10, 12, 13
WY	2	0	99,999	1, 3, 4, 5, 6, 10, 13

Source: TRI99 2001

<sup>a</sup>Post office state abbreviations used<sup>b</sup>Amounts on site reported by facilities in each state<sup>c</sup>Activities/Uses:

- |                          |                          |                             |
|--------------------------|--------------------------|-----------------------------|
| 1. Produce               | 6. Impurity              | 10. Repackaging             |
| 2. Import                | 7. Reactant              | 11. Chemical Processing Aid |
| 3. Onsite use/processing | 8. Formulation Component | 12. Manufacturing Aid       |
| 4. Sale/Distribution     | 9. Article Component     | 13. Ancillary/Other Uses    |
| 5. Byproduct             |                          |                             |

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reactors is  $1.7 \times 10^7$  Ci. The postirradiation cobalt content of typical PWR and BWR reactor fuel assemblies are 38 g (0.01%) and 26 g (0.01%), respectively.

$^{55}\text{Co}$  may be produced by applying 12 MeV indirect deuteron energy to  $^{54}\text{Fe}$  ( $^{54}\text{Fe}(\text{d},\text{n})^{55}\text{Co}$ ), 40 MeV protons to natural iron ( $^{56}\text{Fe}(\text{p},2\text{n})^{55}\text{Co}$ ), or 20 MeV protons to natural nickel foil ( $^{58}\text{Ni}(\text{p},\alpha)^{55}\text{Co}$ ) followed by separation of the  $^{55}\text{Co}$  on an ion exchange column (Wolf 1955).  $^{57}\text{Co}$  is produced by AEA Technology (formerly Amersham QSA) in the United Kingdom (Web Research Co. 1999).

## 5.2 IMPORT/EXPORT

In 1999, 8,150 metric tons of cobalt was imported into the United States compared with 6,440, 6,710, 8,430, and 7,670 metric tons in 1995, 1996, 1997, and 1998; respectively; 8,000 metric tons of cobalt is estimated to be imported in 2000 (USGS 2000, 2001). Between 1995 and 1998, Norway, Finland, Canada, and Zambia supplied 24, 18, 14, and 13% of cobalt. Imports for 1998 by form included (form, metric tons cobalt content): metal, 6,450; oxides and hydroxides, 868; acetates, 55; carbonates, 8; chlorides, 6; and sulfates 281. Cobalt exports for 1995, 1996, 1997, 1998, and 1999 were 1,300, 1,660, 1,570, 1,680, and 1,550 metric tons, respectively. Exports for 2000 are estimated to reach 2,300 metric tons.

$^{60}\text{Co}$  and  $^{57}\text{Co}$  are produced in Canada and the United Kingdom and are imported from these countries. No import and export quantities for cobalt radioisotopes were available.

## 5.3 USE

The United States is the world's largest consumer of cobalt. Cobalt is used in a number of essential military and industrial applications. The largest use of metallic cobalt is in superalloys that are used in gas turbines aircraft engines. Superalloys are alloys developed for applications where elevated temperatures and high mechanical stress are encountered. It is also used in magnetic alloys and alloys that are required for purposes requiring hardness, wear resistance, and corrosion resistance. Cobalt is used as a binder for tungsten carbide (cemented carbides) cutting tools to increase impact strength. Cobalt compounds are used as pigments in glass, ceramics, and paints; as catalysts in the petroleum industry; as paint driers; and as trace element additives in agriculture and medicine.

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Over 40% of nonmetallic cobalt is used in catalysis and most cobalt catalysts are used in hydrotreating/desulfurization in the oil and gas industry, the production of terephthalic acid and dimethylterephthalate, and the high pressure OXO process for the production of aldehydes. Cobalt chemicals primarily used as catalyst include cobalt(III) acetate, cobalt(II) bromide, carbonate, manganate, oxalate, and sulphide, cobalt carbonyl, and cobalt naphthenate. Cobalt carbonate and chromate are mainly used as pigments and cobalt(II) acetate, 2-ethylhexanoate, linoleate, naphthenate, nitrate, oleate, and stearate are mainly used as driers. Cobalt has been used for hundreds of years as a blue colorant in glass, ceramics and paints.

A growing use for cobalt is as an addition to the Ni/Cd, Ni-metal hydride battery or as the main component of the lithium ion cell ( $\text{LiCoO}_2$ ). In 1999, the reported U.S. cobalt consumption was 8,420 metric tons with a use pattern was (end use, metric tons cobalt content, percent): superalloys, 3,830, 45.5%; steel alloys, 154, 1.8%; other alloys, including magnetic alloys, 1,085, 12.9%; cemented carbides, 755, 9.0%; chemical and ceramic use, 2,530, 30.0%; and miscellany, 64, 0.76%. Cobalt is also used a target material in electrical x-ray generators (Cobalt Development Institute 2000; Donaldson 1986; Hodge 1993; IARC 1991; Richardson 1993; USGS 1998).

Gamma rays from  $^{60}\text{Co}$  are used to sterilize medical and consumer products, to cross-link, graft and degrade plastics, and as an external source in radiography and radiotherapy. In addition,  $^{60}\text{Co}$ , along with iridium-192, is the most commonly used isotope in radiography. In this application,  $^{60}\text{Co}$  is used for nondestructive testing of high-stress alloy parts, such as pipeline weld joints, steel structures, boilers, and aircraft and ship parts. Radiography may be conducted at permanent, specially shielded facilities or temporary sites in the field (NRC 1999).  $^{60}\text{Co}$  is used in chemical and metallurgical analysis and as a tracer in biological studies. In 1990, about 95% of installed  $^{60}\text{Co}$  activity was used for the sterilization of medical devices; about 45% of medical devices were sterilized using radiation.  $^{60}\text{Co}$  is also a source of gamma rays used for food irradiation; depending on the dose levels, irradiation may be used to sterilize food, destroy pathogens, extend the shelf-life of food, disinfest fruits and grain, delay ripening, and retard sprouting (e.g., potatoes and onions). Sludge, waste water, and wood may also be treated with gamma rays to kill harmful organisms.

$^{57}\text{Co}$  decays to an excited state of  $^{57}\text{Fe}$ , the most widely used x-ray source in Mössbauer spectroscopy (Hodge 1993; Richardson 1993). It is also made into standards and sources for dose calibrators, gamma cameras, and gauges, and is used as markers and rulers to help estimate organ size/location. It is also used in *in vitro* diagnostic kits for the study of anemia related to vitamin  $\text{B}_{12}$  deficiency/malabsorption



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(MDS Nordion 2000).  $^{55}\text{Co}$ -bleomycin has been used for scanning malignant tumors (e.g., lung and brain cancer) and is a practical isotope for positron emission tomography (PET) studies because it mainly (81%) decays by positron emission.

#### 5.4 DISPOSAL

There is a paucity of data on the methods of disposal of cobalt and its compounds. Due to the lack of natural sources of economically extractable ores in the United States, cobalt is entirely imported in the United States, and it is considered a strategic mineral. It is economical to recycle certain cobalt wastes rather than to dispose of them. Recycling of superalloy scrap is an important method for the recovery of cobalt. About 2,800 metric tons of cobalt were recycled from purchased scrap in 2000. This was about 33% of reported consumption for the year. According to the Toxic Chemicals Release Inventory (TRI98 2000), 4.42 and 9.01 million pounds of cobalt and cobalt compounds were recycled on-site and off-site, respectively, in 1998. Waste containing cobalt dust and, presumably, waste containing cobalt in the solid state may be placed in sealed containers and disposed of in a secured sanitary landfill (HSDB 1989).

Waste water containing cobalt can be treated before disposal, for instance, by precipitation of carbonate or hydroxide of cobalt or by passage through an ion-exchange resin (Clifford et al. 1986). According to the Toxic Chemicals Release Inventory (TRI99 2001), 1,296,686 pounds of cobalt and cobalt compounds, was transferred off-site for disposal, including solidification/stabilization and waste water treatment, including publicly operated treatment plants (POTWs). The amount of cobalt so transferred by state is shown in Table 6-1.

In August 1998, EPA issued a final rule listing spent hydrotreated and hydrorefined catalysts as hazardous waste under the Resource Conservation and Recovery Act (USGS 1998). Listing under this act requires that releases of these substances will be subject to certain management and treatment standards and emergency notification requirements. Information regarding effluent guidelines and standards for cobalt may be found in Title 40 of the Code of Federal Regulations, Parts 421.230, 421.310, and 471.30.

$^{60}\text{Co}$  sources used for irradiation purposes are valuable and would not be discarded. However, some radioactive cobalt isotopes may occur in waste material from nuclear reactors. Radioactive waste is categorized according to origin, type of waste present, and level of activity. Radioactive cobalt isotopes may be commingled with other radioactive isotopes. The first distinction in radioactive waste is between defense waste and commercial waste, the former being generated during and after World War II

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principally at the Department of Energy (DOE) facilities at Hanford, Washington; Savannah River, South Carolina; and Idaho Falls, Idaho, where plutonium and other isotopes were separated from production reactor spent fuel or nuclear-powered naval vessels. Commercial wastes are produced predominantly by nuclear power plants as well as the long defunct commercial reprocessing facility at West Valley, New York and manufacturers of radioisotopes used in nuclear medicine for the treatment and diagnosis of disease. Nuclear waste is also classified as high-level waste (HLW), transuranic waste (TRU), and low-level waste (LLW). LLW is further differentiated into three classes, A, B, and C, according to increasing of the level of activity. A fourth category, commercial greater-than-class-C LLW (listed in 10 CFR 61.55 Tables 1 and 2 for long and short half-life radionuclides, respectively) are not generally suitable for near-surface disposal. This could include operating and decommissioning waste from nuclear power plant and sealed radioisotope sources. The final disposition for this waste is not known. If LLW also contains nonradioactive hazardous material (i.e., that which is toxic, corrosive, inflammable, or explosive) it is termed mixed waste. Mine tailings from uranium mining is still another category of radioactive waste (DOE 1999; Murray 1994). While radioactive cobalt would not ordinarily be found in HLW or TRU, the definitions of these are included below for completion.

TRUs are those containing isotopes, like plutonium, that are above uranium in the periodic table whose half-lives are >20 years. If their level of activity was <100 nanocuries of alpha-emitters per gram of waste material (up from 10 nanocuries/g in 1982), the waste could be disposed of by shallow burial. Otherwise, the waste had to be placed in retrievable storage for eventual transfer to a permanent repository. The level of radioactivity in TRUs is generally low, they generate very little heat, and can be handled by ordinary means without remote control (Eisenbud 1987, Murray 1994).

HLW includes spent fuels which are contained in fuel rods that have been used in a nuclear reactor. These may contain small amounts of transuranic elements. After removal, these rods are placed in pools adjacent to the commercial nuclear power plants and DOE facilities where they were produced. It was originally intended that the fuel rods remain in these pools for only about 6 months to allow for a reduction in radioactivity and temperature and then be transferred to a reprocessing or storage facility. There are no commercial reprocessing facility or permanent disposal facility for HLW operating in the United States. The Nuclear Regulatory Commission (NRC) has issued standards for the disposal of HLW (10 CFR 60), and the DOE is pursuing the establishment of an HLW facility in Yucca Mountain, Nevada. Efforts to establish an HLW facility, which began over 2 decades ago, have experienced many delays. A facility for the permanent disposal of HLW is not projected to be in operation before 2010 (Eisenbud 1987; Murray 1994).

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LLWs are officially defined as wastes other than those previously defined. These wastes come from certain reactor operations, manufacturers of radioisotopes used in nuclear medicine and institutions such as hospitals, universities, and research centers. Most LLW contain very little radioactivity and contain practically no transuranic elements. It requires little or no shielding or special handling and may be disposed of by shallow burial. However, some LLW contains sufficient radioactivity as require special treatment. Although NRC regulations for LLW disposal (10 CFR 61) permit shallow land burial, many states have enacted more stringent regulations that require artificial containment of the waste in addition to natural containment (Eisenbud 1987; Murray 1994). The EPA has proposed regulations for LLW disposal that would apply to DOE facilities (EPA 1998b). The Manifest Information Management System (MIMS) maintained by the Idaho National Engineering and Environmental Laboratory, contains information on low-level radioactive waste shipments received at commercial low-level radioactive waste disposal facilities at Barnwell, South Carolina (1/1/86-present), Beatty, Nevada (4/1/86-12/31/92), Richland, Washington(1/1/86-present), and Envirocare, Utah (1/1/98-12/31/99). In 1999, 17 Ci of  $^{57}\text{Co}$ , 1,300 Ci of  $^{58}\text{Co}$ , 0.02 Ci of  $^{59}\text{Co}$ , and 1,080,000 Ci of  $^{60}\text{Co}$  contained in LLW was received at these facilities from academic, industrial, government, and utility generators throughout the United States (INEL 2000). In addition, 4.26 Ci of  $^{57}\text{Co}$  of NARM (“naturally occurring and accelerator-related waste”) was received.

At present, DOE stores most of its spent fuel at three primary locations: the Hanford site, Washington, the Idaho National Engineering Laboratory, Idaho, and the Savannah River site, South Carolina. Some spent fuel is also stored at the dry storage facility at Fort St. Vrain in Colorado. Much smaller amounts of spent nuclear fuel stored at other sites were to be shipped to the three prime sites for storage and preparation for ultimate disposal (DOE 1999). The DOE National Spent Fuel Program maintains a spent nuclear fuel data base that lists the total volume, mass and metric tons heavy metal (MTHM) of 16 DOE categories of spent nuclear fuel stored in each of the three locations. The categories having the highest  $^{60}\text{Co}$  activities per spent nuclear fuel canister (decayed to 2030) are ‘naval surface ship fuel’ and ‘naval submarine fuel’. The  $^{58}\text{Co}$  and  $^{60}\text{Co}$  solid waste stored on the Hanford site in 1998 as LLW was 2,600 and 6,900 Ci, respectively (Hanford 1999). In addition, 40 Ci of  $^{60}\text{Co}$  was included in TRU.

In commercial irradiators, additional quantities of  $^{60}\text{Co}$  are added, usually once a year to maintain preferred energy levels of the source (MDS Nordion 2000).  $^{60}\text{Co}$  sources are removed from the facility at the end of their useful life, which is typically 20 years. In general, manufacturers of  $^{60}\text{Co}$  sources guarantee to accept the sources they originally supplied. These old sources may be reencapsulated, reprocessed, or recycled when technically, environmentally, and economically feasible.